

# CC $\pi^0$ Event Reconstruction at MiniBooNE

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**Abstract.** We describe the development of a fitter to reconstruct  $\nu_\mu$  induced Charged-Current single  $\pi^0$  (CC $\pi^0$ ) events in an oil Čerenkov detector (CH<sub>2</sub>). These events are fit using a generic muon and two photon extended track hypothesis from a common event vertex. The development of ring finding and particle identification are described. Comparisons between data and Monte Carlo are presented for a few kinematic distributions.

**Keywords:** neutrino, neutrino interactions, charged current single pion

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## INTRODUCTION

Experimental measurements of the charged-current neutral pion (CC $\pi^0$ ) mode are of interest to the community for several reasons. First, like charged-current quasi-elastics (CCQE) a CC $\pi^0$  event only scatters off of the neutrons in a nucleus. Second, there is no coherent interaction, so this channel uniquely probes incoherent pion production. Third, CC $\pi^0$  events are a small background for experiments that intend on using CCQE to search for neutrino oscillations. As these measurements get more precise, a more accurate background prediction is required. Finally, this measurement has orders of magnitude more statistics than previous measurements which will allow for the measurement of various, previously unmeasured, differential cross-sections.

This note describes the development of a three-(Čerenkov)ring fitter needed for the measurement of CC $\pi^0$  differential cross-sections. The experiment is described along with the observable signal. The development of the fitter is detailed, an event sample is isolated, and various kinematic distributions are shown for both data and Monte Carlo (MC).

## MiniBooNE

The Mini-Booster-Neutrino-Experiment (MiniBooNE) is described in detail in Ref. [1]. The apparatus consists of a pulsed neutrino beam originating 500 meters away from an 800 ton, spherical, oil Čerenkov detector. The neutrino beam is a mostly pure  $\nu_\mu$  beam with peak energy of  $\sim 700$  MeV with the majority of the flux below 1500 MeV [2]. The detector is divided into two optically isolated regions; an inner detector region 575 cm in radius surrounded by 1280 8-inch photo-tubes (11.3% photo-cathode coverage), an outer veto region that extends to 610.6 cm in radius monitored by 240 photo-tubes.

A basic event classification in the MiniBooNE data stream takes advantage of the pulsed nature of the neutrino beam. A typical event in the tank produces enough light during a short time to be detected by some fraction of the photo-tubes. A cluster of these hits in a narrow time window is called a “subevent.” A neutrino event may have any number of subevents within the beam time window. The prompt neutrino interaction produces one subevent; subsequent stopped muon decays produce additional subevents. For example, muon-CCQE events differ from electron-CCQE events in that they ideally have 2 subevents (one from the initial neutrino interaction, the second from the electron from the muon decay), where an electron-CCQE should have only one subevent. These idealizations can break down ( $\mu^-$  capture, a coincident cosmic ray, a muon decay during the first subevent, etc.), nevertheless as a basic classifier, dividing events by the number of subevents separates out the various classes of events. A CC $\pi^0$  event is expected to have 2 subevents. The largest background, CC $\pi^+$  events, are expected to have 3 subevents.

The MC simulations of pion production in the MiniBooNE detector are based on the Rein-Sehgal model [3] with an  $M_A = 1.1$  GeV [4]. The Smith-Moniz formalism [5] is used for CCQE production with parameters tuned to reproduce the MiniBooNE CCQE data [6].

## Observable $CC\pi^0$ events

To avoid the added complication of trying to extract cross-sections at the nucleon level, an observable signal is defined. The goal is to avoid the model dependencies associated with trying to extend what is experimentally observable (particles that emerge from the target nucleus) to what occurred at the initial neutrino interaction. The “observable  $CC\pi^0$ ” signal is defined as a muon plus a  $\pi^0$  that exited the target nucleus (carbon) with no other mesons. This not only includes “true”  $CC\pi^0$  events (70%) [4], but also  $CC\pi^+$  events that charge-exchanged ( $\pi^+ \rightarrow \pi^0$ ) within the target nucleus (21%), CCQE events (6%), and a remainder of NC and CC multi-pion events. It is important to note that any  $\pi^0$  created outside of the initial target nucleus, through  $\pi^+$  and nucleon reinteractions in the mineral oil, is not considered an observable  $CC\pi^0$  event. These events are referred to as “tank- $\pi^0$ ” events.

## EVENT RECONSTRUCTION

MiniBooNE incorporates an extended-track, maximum likelihood method for event reconstruction [7]. A track is characterized by 7 parameters: the event vertex ( $x, y, z$ ), the time ( $t$ ), direction ( $\theta, \phi$ ), and kinetic energy ( $E$ ). The Čerenkov and scintillation light produced by a track are separated into prompt and late portions. The generated light is then propagated through the mineral oil via an extensive optical model until the light reaches the photo-tubes. For each PMT, a probability is assigned to address whether the tube was hit, the time of the hit, and the resulting deposited charge. These probabilities are compared with the measured charge and time associated with each tube. The hit times are dominated by the Čerenkov light. The charges are simply the sum of the scintillation and Čerenkov portions. The track parameters are varied and the maximum likelihood is chosen to best describe the track parameters. In practice, the minimum of the negative logarithm of the likelihood is used. This way the time and charge likelihoods can be calculated separately and then added together to get the total likelihood. The light profiles for different types of particles (in this case  $\mu$  or  $e/\gamma^1$ ) are used to distinguish between event types.

For multiple tracks, the likelihoods for each track can be combined. The charge likelihoods can be simply added together. The time likelihoods are weighted conditionally by the closest track (defined by the track’s mid-point), then added together. The number of parameters for multi-track events depend on the event type. For a  $CC\pi^0$  event hypothesis, it is assumed that the  $\pi^0$  decays to 2 photons immediately<sup>2</sup>. The signature of these events is a muon and 2 photons that come from a common vertex. Therefore, there are 15 parameters to fit: the event vertex ( $x, y, z$ ); the time ( $t$ ); the muon’s energy and direction ( $E_\mu, \theta_\mu, \phi_\mu$ ); and the photons’ energy, direction, and conversion length ( $E_i, \theta_i, \phi_i, s_i$  where  $i = \gamma_1, \gamma_2$ ).

Tracks are searched for in a step-wise fashion. A one-track fit is performed, which finds one of the three tracks. While keeping that track fixed in the likelihood function, a scan of 400 points in solid angle with a 200 MeV (chosen at the peak of the photon energy spectrum) second track about the event vertex is performed. The best likelihood from the scan is chosen, and all parameters (except the conversion lengths) are allowed to float for the two tracks. The two tracks are then fixed in the likelihood function and the full solid angle is scanned for a third track. The best likelihood is then used as a seed for a three-track fit (again, no conversion lengths). Once the event vertex, track directions, and rough estimates for the track energies are found, three fits are then performed in parallel. These fits swap out two of the tracks for photons seeded with conversion lengths of 50 cm (roughly the radiation length in oil) This is done for the three possible particle type configurations. One of the three fits then gets selected as the final fit based on the fit likelihood and whether the muon track points toward the electron vertex in the second subevent.

## Cuts

Due to the long processing time per event, the two subevent sample must be reduced to a more manageable size before this fitter is run. Since various one-track fits were already run on the sample, they can be used reduce the CCQE contamination. Most of the events in the sample are muon-CCQE. This implies that they should look more like a muon than an electron. Electrons tend to produce fuzzy rings while muons are more rigid. To a fitter that only

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<sup>1</sup> The difference between electrons and photons is that photons travel some distance before they produce a track similar to electrons.

<sup>2</sup> Branching fraction of  $\pi^0 \rightarrow \gamma\gamma$  is 98.8% [8].

**TABLE 1.** This table is divided into two sections. The first section divides the sample into the absolute modes from the NUANCE [4] predictions. The second section divides the sample into the observable  $CC\pi^0$  signal, and the tank  $\pi^0$ . The first column shows the predicted event numbers with the basic cuts along with the purity in parentheses. The second column adds the event filter and analysis cuts and shows the efficiencies relative to the first column along with the purity in parentheses. The final sample is divided between signal and background with a 26% signal efficiency.

MC Sample	2SE + tank + veto	+ event filter + likelihood + small angle
CCQE	155480 ( 63%)	0.6% ( 10%)
$CC\pi^0$	15615 ( 6%)	19.3% ( 34%)
$CC\pi^+$	62167 ( 25%)	1.4% ( 36%)
everything else	14764 ( 6%)	28.3% ( 20%)
Observable $CC\pi^0$	16098 ( 6%)	25.7% ( 47%)
tank $\pi^0$	15507 ( 6%)	25.5% ( 44%)
everything else	216421 ( 87%)	0.4% ( 9%)
total	248026 (100%)	3.6% (100%)

fits single electrons and muons, a multiple track event would look more like an electron. A cut is applied that selects more electron-like events in the fit likelihood. This cut defines the sample that will be fit by the  $CC\pi^0$  fitter. It is 88% efficient at keeping observable  $CC\pi^0$  events. This reduces the two-subevent sample from  $\sim 250,000$  to only  $\sim 43,500$  events that need to be fit. After the events are fit they are again selected to isolate a purer observable  $CC\pi^0$  sample. Two cuts are applied; a fit likelihood cut that removes events without  $\pi^0$ , and a cut on the smallest angle between the three reconstructed tracks removing events with poorer particle ID. Eventually, a  $\pi^0$  mass cut will be applied to reduce some backgrounds further, and to select well reconstructed observable  $CC\pi^0$  event. However, no mass cut has been applied in this analysis.

Table 1 shows the effects of these cuts. The two subevent sample is mostly CCQE with only a 6.5% observable  $CC\pi^0$  purity. After all the cuts, the sample is reduced by 75%, however, the  $CC\pi^0$  purity increases to 46.4%. Including the two subevent cut (removes  $\sim 60\%$  of observable  $CC\pi^0$  events), this factors in as about a 12% total efficiency for  $CC\pi^0$  events. The CCQE events are reduced to less than 1% efficiency but still comprise 10% of the final sample. Unfortunately, the tank  $\pi^0$  are kept in roughly the same proportions as the signal. They mostly come from  $CC\pi^+$  events that charge exchange in the mineral oil and are the largest background. The remaining tank  $\pi^0$  background are mostly from CC multi  $\pi$ , NC events, and DIS.

## KINEMATICS

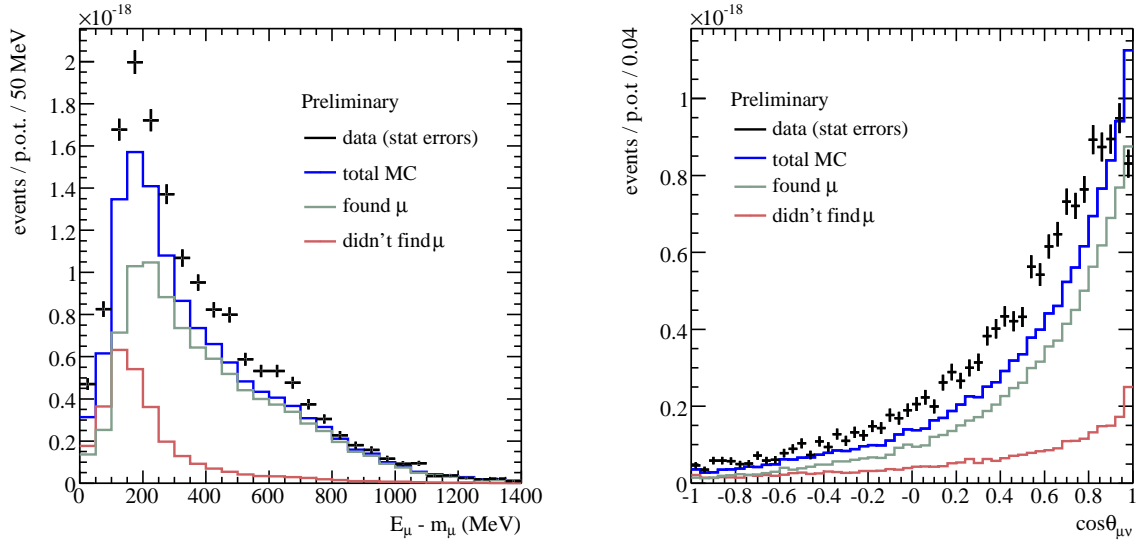
The usefulness of this fitter is ultimately measured by how well it can be used to reconstruct various physics parameters of the event. To that end, it is useful to understand how reconstructing the muon and the two photons can be used to infer the properties of the incident neutrino and the intermediate states. A  $CC\pi^0$  event is of the form  $\nu_\mu n \rightarrow \mu^- p \pi^0 \rightarrow \mu^- p \gamma \gamma$ . Conservation of 4-momentum yields

$$(p_\nu + p_n - p_X)^2 = m_p^2 \quad (1)$$

where  $p_X \equiv p_\mu + p_{\gamma 1} + p_{\gamma 2}$ , replaces the typical lepton momentum used to derive the standard CCQE neutrino energy formula. One particle is replaceable by its invariant mass, in this case the unmeasured proton. Since the fitter measures  $p_X$ , the neutron is assumed to be at rest, the neutrino is assumed to travel in the beam direction, then the neutrino energy is fully specified. The neutrino energy is given by

$$E_\nu = \frac{m_p^2 - m_n^2 - m_X^2 + 2m_n E_X}{2(m_n - E_X + |\mathbf{p}_X| \cos \theta_{\nu X})} \quad (2)$$

where properties of  $X$  are measured in the lab frame. Now that all the initial and final state particles have been fully specified, the  $\pi^0$ ,  $Q^2$ , and the  $\Delta$  resonance internal states can be reconstructed. However, no assumption is made that this is actually a  $\Delta$  resonance (i.e. no mass assumption), it can be any of the 17 resonances in the MC, though the  $\Delta$  is



**FIGURE 1.** The reconstructed muon kinetic energy (left) and the muon angle relative to the neutrino beam (right). The MC is broken up into two samples, one where the particle ID correctly identified the muon (grey), and one where it did not (red). Data is normalized by proton on target (p.o.t.). MC is normalized by the default NUANCE cross-section predictions.

by far the most prominent source at MiniBooNE energies. They are reconstructed through

$$p_\pi = p_{\gamma 1} + p_{\gamma 2} \quad (3)$$

$$Q^2 = -(p_\nu - p_\mu)^2 \quad (4)$$

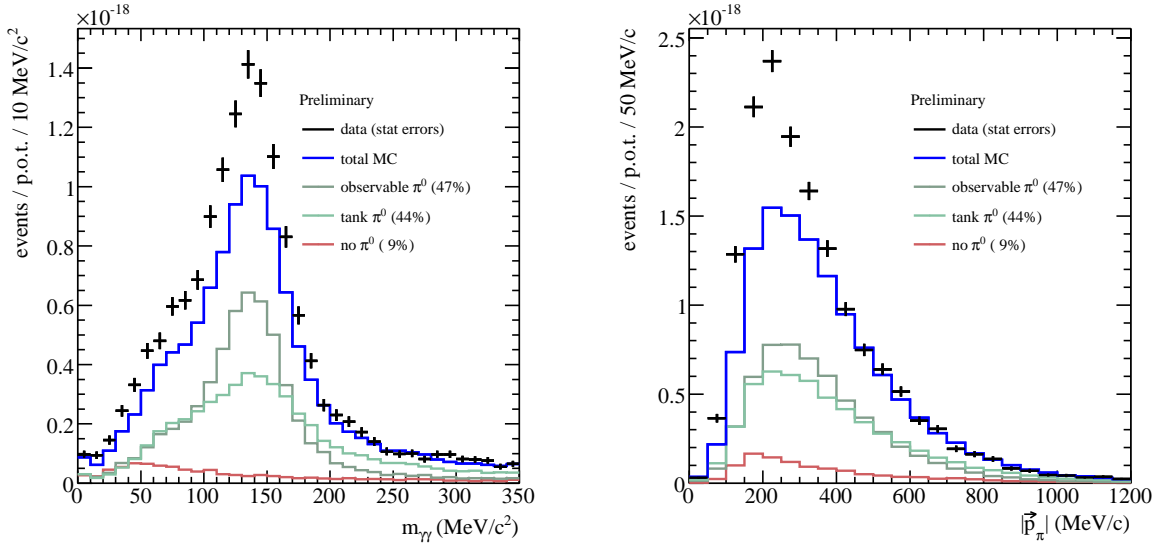
$$p_\Delta = p_\nu - p_\mu + p_n. \quad (5)$$

While the MC appears to underpredict the number of  $CC\pi^0$  events observed in data<sup>3</sup>, most distributions agree fairly well in shape. Fig. 1 shows the reconstructed muon kinetic energy and muon angle relative to the beam. Data and MC agree quite well (in shape) with a muon energy resolution of 9%. Fig. 2 shows the reconstructed pion mass and 3-momentum. The mass plot is striking because of how well the three-track fit matches the known  $\pi^0$  mass when no  $\pi^0$  mass assumptions were used during the fit. Both the mass and the momentum match well in shape. Fig. 3 shows the reconstructed neutrino energy. The neutrino energy matches well even for modes without  $\pi^0$ . This is partly because the neutrino energy is roughly correlated with the total energy deposited in the tank and the fitter does a good job on measuring the total visible light. The neutrino energy resolution is found to be 11%. Finally, Fig. 4 shows the measured 4-momentum transfer,  $Q^2$ . Differences in these distributions probe the model used to predict single pion modes.

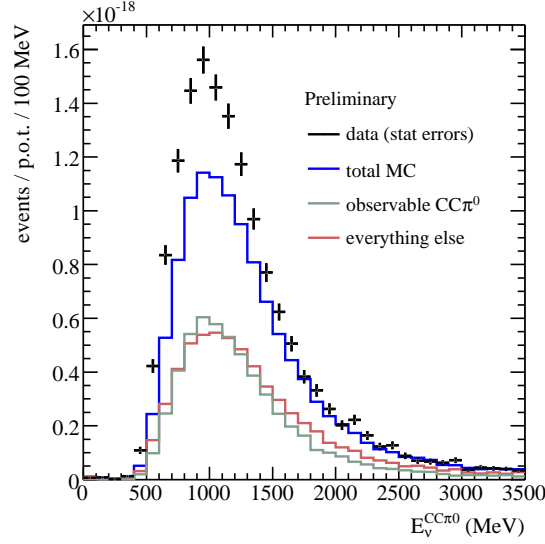
## CONCLUSIONS

A method for reconstructing  $CC\pi^0$  events in a Čerenkov detector has been described. After a reduction of the data to increase the signal purity, a three-track fit was performed. The sample was then further reduce to isolate a purer sample of observable  $CC\pi^0$  events. Since this fitter reconstructs both the muon and the  $\pi^0$  in an event, it has the ability to measure many differential cross-sections. Among the possible measurements will be:  $\sigma(E_\nu)$ ,  $\frac{d\sigma}{dE_\mu}$ ,  $\frac{d\sigma}{\cos\theta_\mu}$ ,  $\frac{d\sigma}{d|\vec{p}_\pi|}$ ,  $\frac{d\sigma}{\cos\theta_\pi}$ ,  $\frac{d\sigma}{dQ^2}$ . Hopefully, this suite of measurements will aid in the understanding of CC single-pion production on nuclear targets.

<sup>3</sup> The normalization difference is consistent with the differences observed in other MiniBooNE CC samples.



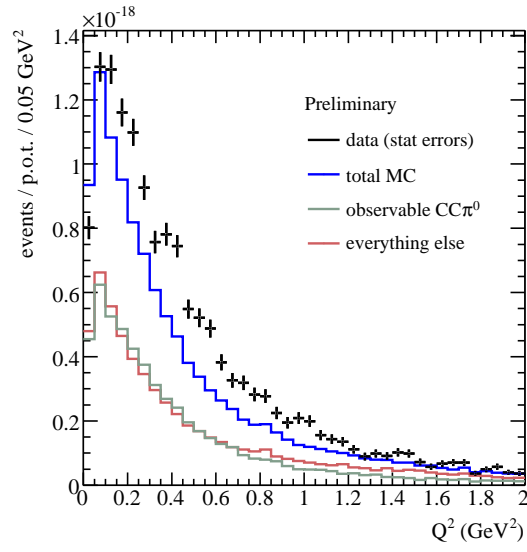
**FIGURE 2.** The reconstructed  $\pi^0$  mass (left) and 3-momentum (right). The MC is divided into three samples; observable  $\text{CC}\pi^0$  (grey), tank  $\pi^0$  (green), and events without a  $\pi^0$  (red). The mass plot shows a nice peaks at the known  $\pi^0$  mass for both the observable and tank  $\pi^0$  cases. Each sample is normalized by proton on target (p.o.t.).



**FIGURE 3.** The reconstructed neutrino energy. The MC sample has been divided into observable  $\text{CC}\pi^0$  (grey) and everything else (red). Each sample is normalized by proton on target (p.o.t.).

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**FIGURE 4.** The reconstructed 4-momentum transfer,  $Q^2$ . Each sample is normalized by proton on target (p.o.t.).

## REFERENCES

1. A. A. Aguilar-Arevalo *et al.*, *Nucl. Inst. Meth. A* **599**, 28 (2009).
2. A. A. Aguilar-Arevalo *et al.*, *Phys. Rev. D*, **79**, 211801 (2009).
3. D. Rein, and L. Sehgal, *Annals of Physics* **133**, 79 (1981).
4. D. Casper, *Nucl. Phys. Proc. Suppl.* **112**, 161–170 (2002).
5. R. A. Smith, and E. J. Moniz, *Nucl. Phys.* **B43**, 605 (1972).
6. A. A. Aguilar-Arevalo *et al.*, *Phys. Rev. Lett.* **100**, 032301 (2008).
7. R. B. Patterson *et al.*, *Nucl. Inst. Meth. A* **608**, 206 (2009).
8. C. Amsler *et al.*, *Phys. Lett. B* **667**, 1 (2008).